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REVIEW OF FLOOD FREQUENCY METHODS

Final Report of the Subcommittee of the Joint Division Committee on Floods

HYDRAULICS DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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REPORTS

REVIEW OF FLOOD FREQUENCY METHODS

FINAL REPORT OF THE SUBCOMMITTEE OF THE JOINT DIVISION COMMITTEE ON FLOODS

Synopsis

This report summarizes the available methods of predicting flood frequencies. It considers the factors affecting the accuracy of such predictions and gives the limitations of the various approaches to the problem.

Introduction

The report gives consideration to definitions of flood probability in common use. It describes the several methods used to construct flood frequency curves including the "basic stage" and the "yearly flood" methods. Particular attention is given to the extrapolation of such curves to indicate the probability or average return period of floods of exceptional magnitude.

The committee concludes that present (1951) methods of determining flood probabilities are suitable for use in connection with cofferdams, highways, and other minor structures, but believes that existing methods which use solely extrapolations of frequency plotting of existing flood records are to be condemned for the determination of the probable frequency of floods for which major structures should be designed, the failure of which would result in a calamity.

Flood Frequency

Definition.—Flood frequency has been variously defined as percent chance[1] and future frequency[2,3,4] and has been related to probability,[5] recurrence interval,[6] and return period[5] of a given flood. Most people are apt to consider

[1] "Flood Flows," by Allen Hazen, John Wiley & Sons, Inc., New York, N. Y., 1930.

[2] "Hydroelectric Handbook," by William P. Creager and Joel D. Justin, John Wiley & Sons, Inc., New York, N. Y., 1927 and 1950.

[3] "Engineering for Dams," by William P. Creager, Joel D. Justin, and Julian Hinds, John Wiley & Sons, Inc., New York, N. Y., 1945.

[4] "A Simple Method of Estimating Flood Frequency," by Ralph W. Powell, *Civil Engineering*, Vol. 13, 1943, p. 105.

[5] "Floods Estimated by Probability Method," by E. J. Gumbel, *Engineering News-Record*, Vol. 134, 1945, p. 833.

[6] "Floods in Ohio, Magnitude and Frequency," by W. P. Cross, *Bulletin No. 7*, Ohio Water Resources Board, Columbus, Ohio, 1946.

that a maximum yearly flood, estimated to have a 1% chance of occurring, or a probability of occurrence of once in 100 years, or a frequency of occurrence corresponding to a recurrent interval (or return period) of 100 years, will occur exactly once each 100 years; and that, having occurred, it will not occur again for another 100 years. This opinion is, of course, entirely wrong.

In order to remove this confusion of thought, the following definitions and limitations are suggested:

The percentage frequency of a given flood may be defined as the percent of observed floods that were equal to, or larger than, a given flood within the period of records under observation. It also may be used as the estimated percent of floods that will be equal to, or larger than, a given flood. It corresponds to the percent chance.

The recurrence interval and return period of a given flood may be defined as the average interval of time within which the flood will be equaled or exceeded once in the mean. It must be understood that when the frequency of a given flood magnitude is expressed by the return period, the computed period is solely an average, and the next such period may experience none, one, or more than one flood equal to or greater than the given flood.

As a matter of theory, if the basic data are truly representative, a flood having a return period of 100 years will be equaled or exceeded in a great length of time, on an average of once in 100 years. With 10,000 years of record there would be 10,000/100 or 100 such floods. However, if these 10,000 years were divided into 100 periods of 100 years each, about 37% of such periods would not experience that flood; about 37% of the periods would experience one such flood; about 18% would experience 2; about 6% would experience 3; about 1.5% would experience 4; and about 0.5% would experience 5 or more such floods.

Flood Frequency in General.—Methods have been devised for the determination of the probable frequency of floods based on records of stream flow. Such methods ordinarily make use of frequency curves that have been well described in the literature.[6,7,8] They are applicable to the determination of the frequency of floods for cofferdams, highways, and other minor structures (in which flood damage would entail a financial loss and inconvenience but would not be classed as a calamity) and to solve the problem of economic justification of flood control programs. However, in the United States and some other countries there is a lack of records of stream flow covering a period of sufficient length; hence, such methods are not applicable to the determination of the probable frequency of floods for which major structures should be designed and whose failure would be classed as a calamity.

This subcommittee has devoted much time to the question of the frequency of such large floods. As a result of such studies the conclusion reached was that no method has yet been devised that can be used to indicate the probable frequency of such floods. It is the consensus among those who have given considerable study to the subject that existing methods depending only on

[7] "Hydrology Handbook," *Manual No. 28*, ASCE, 1949.

[8] "Floods of May-June, 1948 in Columbia River Basin," *Water Supply Paper No. 1080*, U. S. Geological Survey, U. S. Govt. Printing Office, Washington, D. C., 1949.

extrapolations of frequency plotting of existing flood records, are inadequate for use in determining flood frequencies. However, these methods are still being used by some engineers in the United States and abroad.

Flood Frequency Curves.—In the process of collecting flood data on a river many ordinary floods are recorded during a long period of time during which occasional extreme high floods will be recorded. The resulting series of flood events is analyzed by the application of the theory of probability. This consists of calculating and plotting the percentage chance (or the return period) of all the floods in the series, and by eye or by a mathematical process, drawing a regular curve or, in special cases, a straight line through such plotted points. Such a curve is a frequency curve and is usually well defined in its central portion but is likely to be poorly defined at the upper end. This condition often prevents extension of the curve with a dependable degree of accuracy.

The calculation for plotting the points for the frequency curve can be made by either the annual flood method (sometimes called the yearly flood method) or the basic flood method (sometimes called the basic stage method or partial duration series). The fundamental principles of analysis in each of these methods is the same. In the annual flood method only the maximum flood during each year of record is used and the advantage of the method lies in the fact that statistical analysis can be used. In the basic flood method all floods of record that exceeded a given base flow are used. This involves many more floods and therefore is more tedious to use than the annual flood method. The base flow for the basic flood method is usually taken approximately equal to the lowest annual flood. Each flood to be listed should be the peak of a flood resulting from an independent hydrologic event. Both the annual flood and basic flood methods have their utility, as explained in the following sections of this paper.

In order to derive a general equation for estimating flood frequency, all of the floods of record using either the yearly flood or basic flood methods should be listed in the order of decreasing magnitude, and each should be given a number, M, in a consecutive series. The number M then indicates the number of times that a given flood was equaled or exceeded during the period of records. For the maximum flood of record, therefore, $M = 1$.

If N equals the number of years of record, the estimated return period (T) of a given flood, in years, may be expressed:

$$T = \frac{N + 1}{M} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

If a structure, such as a temporary bridge or a cofferdam, is to be designed to withstand a flood not exceeding one having a return period of about 10 years, the basic stage method of flood prediction should be used. On the other hand, if an extrapolation is to be made as far as possible, such as for the determination of the economic justification for flood control or the elevation of an important building, the yearly stage method involves less work and may be used.

In many instances in studies of flood frequencies one or more floods, either modern or historical, are found to be of much greater magnitude than the

rest. If this flood is given its normal position in the usual probability plotting, the result is a probability curve that, if obtained by any mathematical method, lies below the outstanding flood and considerably higher than all other floods of record. The accuracy of this curve is open to question. There is a divergence of opinion as to the proper method of treatment of these great floods. In drawing the curves these floods may be given only little weight by raising the curve according to judgment, but this provides no specific basis for the location of the curve, and each investigator would draw a different curve. A more logical practice is to recognize that these great floods have a return period much longer in years than the length of record and to draw the curve without regard to them. Points representing these floods would then be plotted on an extension of the frequency curve and the indicated return period would show the most probable frequency of that flood. It is believed by some that such outstanding floods follow some law of their own that comes into operation at very long intervals. Whether or not they follow their own or the usual laws, it would seem obvious that they cannot be assumed to have a return period equal to the length of the records.

Extrapolation of Frequency Curves.—If the floods are plotted on rectangular coordinate paper, a frequency curve drawn through them may show exceeding curvature and be difficult of extrapolation by eye. Such interpolation is necessary in order to estimate the frequency of floods having a return period considerably greater than the length of record. If plotted on some form of probability paper, or on semilog or log-log paper, the curvature will be more moderate.

If the plotted points are not too scattered and a line drawn through them is not too curved, a moderate extrapolation of the line can be made by eye, within the accuracy of available data. If the line is quite curved when plotted on probability or log paper, it still can be used.[9] By trial a constant q must be determined that is added to or subtracted from all the ordinates of the curve. The new curve so obtained will approach a straight line that can be more accurately extrapolated. If the points are quite scattered, or if a more precise extrapolation is desired, there are available many mathematical procedures, based on the different laws of probabilities, for plotting the probability curve and its extrapolation. A historical review of the many different methods suggested for the determination of flood frequency may be found in publications of the United States Geological Survey (USGS).[10,8]

It is not within the scope of this report to describe concisely the methods proposed for calculating mathematically the probability curve of floods. The procedure recommended by A. Hazen,[1] based on the method proposed by H. Alden Foster, M. ASCE,[11] is still in use. E. J. Gumbel[5] has devised a probability paper adaptable only to the annual flood method on which the frequency curve theoretically will be a straight line.

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[9] "Straight Line Plotting of Skew Frequency Data," by R. D. Goodrich, *Transactions*, ASCE, Vol. 91, 1927, p. 1.

[10] "Floods in the United States, Magnitude and Frequency," *Water Supply Paper No. 771*, U. S. Geological Survey, U. S. Govt. Printing Office, Washington, D. C., 1936.

[11] "Theoretical Frequency Curves and Their Application to Engineering Problems," by H. Alden Foster, *Transactions*, ASCE, Vol. 87, 1924, p. 142.

There is a practical limit to the extent to which a simple frequency curve can be extrapolated with reasonably accurate results. The extreme limit of extrapolation for frequency curves in modern practice is that required for determining the economic justification of flood control projects. In such cases the necessity arises to estimate the magnitude of a flood that has a return period of 100 or 200 years, and extrapolations to 3 or 4 times the period of record have been required. This is justified only where there is no other method of analysis.

In Massachusetts, a process of analysis applicable to rivers in that area has been made by H. B. Kinnison, M. ASCE, and B. R. Colby.[12] This process provides the means of extending frequency curves to a computed maximum possible flood arbitrarily plotted at a return period of 100,000 years. Intermediate points on the frequency curve for major and rare floods (for convenience called the 100-yr and 1,000-yr floods respectively) are computed from a frequency study of great storms combined with a study of rainfall-runoff relations and the application of the unit hydrograph. The maximum possible flood is likewise computed by the application of the unit hydrograph to the maximum possible precipitation, determined by the application of physical laws to the atmosphere and computed and published by the Weather Bureau, United States Department of Commerce.[13] By passing the frequency curve through the points plotted at the lower end of each curve and thence through the computed points for the major, rare, and maximum possible floods, a complete frequency curve is prepared that, it is claimed, makes it possible to estimate the frequency of all floods. The results of this work are applicable only to the area studied, and the accuracy is limited by incomplete data and short records.

Use of Historic Floods

Properly authenticated historic floods, antedating periods of consecutive records, can be used to widen immeasurably the horizon in regard to the frequency of occurrence of floods. The first systematic effort at authentication of historic floods was undertaken by the State Water Supply Commission of Pennsylvania in 1913.[14] Since that time good progress on the compilation of historic floods has been made by federal agencies and Army district engineers in connection with studies on flood control projects. Other researches are referred to in the literature[15,16,17,18] and in various flood control reports of the

[12] "Flood Formulas Based on Drainage Basin Characteristics," by H. B. Kinnison and B. R. Colby, *Transactions*, ASCE, Vol. 110, 1945, p. 849.

[13] "Generalized Estimates, Maximum Possible Precipitation Over the United States, East of the 105th Meridian," *Hydrometeorological Report No. 23*, Weather Bureau, U. S. Dept. of Commerce, Washington, D. C., June, 1947.

[14] "Floods," *Water Resources Inventory Report*, Water Supply Commission of Pennsylvania, Part VIII, 1917.

[15] "The Floods of March 1936," *Water Supply Papers Nos. 798, 799, and 800*, U. S. Geological Survey, U. S. Govt. Printing Office, Washington, D. C., 1937.

[16] "The Floods of Ohio and Mississippi Rivers, January–February, 1937," *Water Supply Paper No. 838*, U. S. Geological Survey, U. S. Govt. Printing Office, Washington, D. C., 1938.

[17] "Stages and Flood Discharges of the Connecticut River at Hartford, Conn.," by H. B. Kinnison, L. F. Conover, and B. L. Bigwood, *Water Supply Paper No. 836-A*, U. S. Geological Survey, U. S. Govt. Printing Office, Washington, D. C., 1938.

[18] "Statistical Forecast of Floods," by E. J. Gumbel, *Bulletin No. 15*, Ohio Water Resources Board, 1949.

War Department published in House Documents. Historic floods have also been recorded in the USGS Water Supply Papers for particular drainage areas.

In the course of time, the value of data of this kind has become recognized, and former skepticism has given way to extended research. Therefore, many of the older records that have ceased to supply usable flood data as the result of artificial regulation have now become enhanced in value by revision backward to include historic floods. Estimated discharge based on authenticated stages of historic floods that occurred prior to a period of continuous records may be used in connection with the continuous records to obtain a more accurate probability curve.

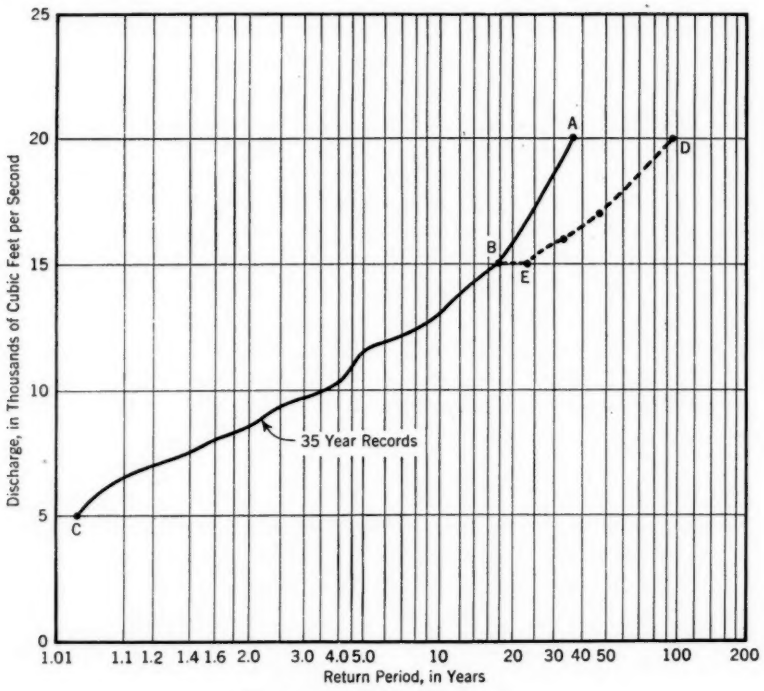

FIG. 1.—USE OF HISTORIC FLOODS

Assume that 35 years of flood records for a stream are available from 1910 to 1944. Line ABC in Fig. 1 indicates the frequency curve for that period of records obtained by usual methods. Assume now that the total number of occurrences of all floods equal to or exceeding a given flood (say 15,000 cu ft per sec) for the 95-yr period preceding 1944 have been definitely established from flood marks on buildings or other conclusive evidence. The upper section of a 95-yr frequency curve can then be established enveloping all floods equal to or exceeding 15,000 cu ft per sec. This part of the 95-yr frequency curve is just as accurate as though all the floods during the 95 years were known. It is calculated in the following table and is plotted in Fig. 1 as line DE.

The flood of 15,000 cu ft per sec is common to both the 95-yr and the 35-yr frequency curves and is represented by the line EB. It now remains to smooth out line DEBC for extrapolation by eye (not shown) to determine the frequency of floods larger than that indicated by point D. This method is purely empirical and cannot be incorporated in strictly mathematical analyses

TABLE 1.—CALCULATION FOR HISTORIC FLOODS

Year	Designation	Discharge (cu ft per sec)	Order of magnitude (M)	Return period (T) (yr)	Figure 1 point
		(a) RECENT RECORDS (N = 35)			
1933	Records	20,000	1	36	A
1915	Records	15,000	2	18	B
etc.	Records				
1912	Records	5,000	35	1.03	C
		(b) TOTAL FLOODS (N = 95)			
1933	Records	20,000	1	96	D
1850	Historic	17,000	2	48	...
1882	Historic	16,000	3	32	...
1915	Records	15,000	4	24	E

of the types referred to previously. The greater the number of historic floods, the farther will line DE project towards point C and the greater the ease of combining the two curves.

GENERALIZED FLOOD FREQUENCY RELATIONS

Frequencies on Ungaged Areas.—Computed flood frequency relations obtained from analysis of records on gaged areas may often be correlated for the purpose of estimating flood frequencies at points on the same stream or on streams in adjacent drainage basins. The procedure is to assemble all available frequency curves and to choose the discharge (preferably in cubic feet per second per square mile) at certain selected frequencies corresponding to 10, 25, 50, and 100 years. The discharge for floods of equal frequency are plotted against the corresponding drainage areas in square miles. The resulting plot will produce a family of generally parallel curves, establishing a relationship between discharge and drainage area with frequency as a parameter. The estimated frequency of floods on an ungaged area may be obtained by entering the plot at the proper drainage area and picking off the discharges at the selected frequencies. The interpolated data can then be used to plot a continuous curve of estimated frequencies for the ungaged area. The curves can also be used to determine the probable reliability of a frequency curve obtained from a very short record on a gaged area. In plotting and utilizing such generalized relations it should be reasonably certain that all the gaged and ungaged areas under consideration have similar hydrologic, topographic, and geologic characteristics; otherwise the procedure can lead to very unreliable results.

Volume Frequency.—The frequency with which various volumes of flood runoff (expressed in cubic feet per second per day, acre-feet, or inches of runoff) are equaled or exceeded is important in analyzing the future operation of dams when appreciable volumes of flood runoff are to be stored temporarily, or in flood control studies in which a reservoir is required to control a flood of specified frequency. An approach to the volume frequency can be made by probability curves plotted in accordance with methods previously described for flood peak flows, and such methods have been used.

The volume of runoff for each flood, analyzed with respect to duration as described hereinafter, can be determined and plotted on probability paper and a frequency curve obtained. It is therefore possible to determine the return period of a given flood volume as well as the return period of a given flood peak, but the volume and peak of a known flood will rarely have the same computed frequency. Volume frequency data obtained without regard to the duration of the various floods analyzed are of limited value. The most useful analysis approach is to establish the relationship between the three variables (depth, duration, and frequency) in the same way that rainfall data are analyzed for use in urban storm-water runoff studies. For example, in analyzing the records of a number of independent flood hydrographs over a period of years, all the greatest one-day (or preferably the maximum 24-hr) runoff volumes are tabulated and a frequency relation established. Then the maximum two-day volumes are selected and so on up to durations of ten days or more. The selection of significant durations of runoff depends upon the size and runoff characteristics of the areas under consideration. For very small areas perhaps the volumes should be tabulated for intervals of less than one day in duration.

After a series of frequency curves have been established for flow volumes of various durations, the data can be cross-plotted so that volume is plotted against duration with frequency as a parameter. As in the case of depth, duration, and frequency data for rainfall, it is very unlikely that volumes of equal frequency for all durations will occur in the same flood, but such an assumption is on the conservative side. In fact, for estimates of frequency of reservoir filling, the volume-duration curve can be used as a mass curve of inflow to the reservoir with satisfactory results.

If the storage behind a dam or above a spillway crest is sufficient to materially modify the peak discharge of a flood, the shape of the inflow hydrograph becomes less important than the volume of the flood, and hence the question of the frequency of the peak discharge is not important. However, in low dams with no appreciable storage, the peak discharge governs the ultimate height to which the water will rise. The probable relation between the frequencies of flood volumes and the frequencies of peak discharges can be determined approximately by computing flood volumes for smaller and smaller units of time and comparing the resulting volume frequency curves with available discharge frequency curves. Identical frequency relations should be obtained if volume frequency and discharge frequency are obtained for identical units of time, such as 1 day.

In a search for data on record volumes, it must be remembered that the maximum flood volume discharge in any year may not be concurrent with the maximum peak discharge in that year and that all floods must be examined for maximum volume. For the large floods of rare occurrence it is no easier to determine frequency of flood volume than to determine frequency of flood peak flow, although an adaption of the Kinnison-Colby method, explained previously, might be used with limitations for determination of volume frequency but not for the shape of the hydrograph.

Effect of Available Period of Records on Flood Frequency Curves.—Minor periodical fluctuations (with periods varying from 10 to 25 years) in average annual temperature, river discharge, maximum yearly floods, and other meteorological conditions have occurred in the past and will occur in the future. Therefore, in each study of flood frequency, a careful inspection should be made to determine if the period of records covered a valley or a peak in such fluctuations. Analyses have been made of long records of floods to determine whether component periods within the long record produce similar flood frequency curves. In most cases the shorter periods do not give the same result as the total record but the difference is not necessarily due to the difference in the lengths of record but rather to the concentration of major floods in certain periods. For example, there were many major floods in the United States in the periods: 1820–1834, 1842–1854, 1861–1875, 1881–1896, 1902–1909, 1913–1922, 1926–1938, and 1942–1949.

If an available record of runoff happened to fall between these periods or includes these periods but not the periods without major floods, the resulting flood frequency curves will be distorted either above or below a curve derived from a record including both wet and dry periods. Thus, it is known that flood records of less than possibly 50 years in length are not, as a rule, true samples of much longer records. It is possible that floods occur in an irregular cyclical pattern instead of in accordance with the laws of pure chance. In that case much of the precise mathematical and statistical analysis that has been recommended for flood frequency determinations will only produce a false impression of accuracy. The purpose of this discussion is to warn engineers to be cautious in applying flood frequency studies and to make sure that an available record is a good representation of the flood history of the general region.

Flood Frequency by Seasons.—Some interest is attached to the knowledge of flood frequency by seasons. Farmers, for instance, are interested in the possibility of floods occurring during the planting and growing season of crops. Contractors are interested in the frequency of floods during the construction season. If the damage done by one flood cannot be remedied until the following year, the yearly stage method of prediction may be used, recording, however, not the yearly maximum flood but the maximum yearly flood occurring during the season in question. If two or more floods in a given season would do more damage than just one flood, the basic stage method should be used, recording not only the maximum yearly seasonal flood but all other seasonal floods that could cause damage.

Errors in Statistical Methods

In preparing graphs for frequency of flood recurrence in the manner herein described, it is assumed that the record information of floods is truly representative and that each point on the graph represents the most common occurrence for the frequency as shown (modal value). If the record information covers a sufficient period of time it is possible to construct control curves indicating the limits of variation from the modal figures within any chosen probability. Such statistical control curves have been published.[19] Another procedure starts from the parameters and gives their limits within any chosen probability. Such limiting values, however, will not embrace all probabilities as there is still a chance that floods will occur beyond such limiting values. (The computations for limiting value is made on the assumption that Poisson's approximation to the binomial expansion is applicable to the distribution of flood frequencies.)

Changing Conditions on Watershed

Present and possible future changing conditions on the watershed should be given careful consideration in the determination of flood frequencies. It is evident that any such changes that result in a greater percentage or more rapid rate of runoff will tend to increase the flood of a given frequency. Among other things, such changed conditions may be due to the removal of forests, and for the smaller drainage areas, the conversion of land to urban uses.

Climatic Changes.—There have been basic climatic changes during the geologic periods, perhaps to a lesser extent during the past 1,000 years.

J. B. Kincer[20] has shown that there has been an over-all trend for rising temperatures for the last century, but no correlation between mean annual temperature and flood magnitude has been found, nor is such a relationship considered probable. In the United States during the period 1932 to 1944 there occurred an exceptional number of large floods. This gave rise to the thought that a change in meteorological conditions had occurred.

Based upon studies by the Subcommittee and the opinions of the best authorities on the subject, it is believed that these phenomena are actually part of a relatively short-term periodical fluctuation in meteorological conditions. It would seem that no permanent climatic changes are taking place that would in any way affect basic engineering assumptions resting on the statistical treatment of climatological data.

Relation of Flood Peaks to Average Daily Discharge.—In the early days of stream gagings the rates of flow were published for the average calendar day, determined very largely from readings of staff or chain gages, often with only one or two observations a day. It is obvious that this method not only often gave incorrect average calendar day flow, but also was far removed from recording accurately the momentary peak of floods. The momentary peak in some cases is in excess of 10 times as great as the average calendar day for small watersheds with rapid runoff characteristics. Similar records are

[19] "On the Plotting of Flood-Discharges," by E. J. Gumbel, *Transactions*, American Geophysical Union, Vol. 24, Part II, 1943, pp. 699-716.

[20] "Our Changing Climate," by J. B. Kincer, *Transactions*, American Geophysical Union, Vol. 27, 1946, pp. 342-347.

published today, although the greatly increasing use of gaging stations equipped with water-stage recorders provides for the determination of the momentary peak as well as a continuous hydrograph of the flood.

The derivation of the peak discharge from records of the average daily discharge, when continuous recording records are not available, can be obtained by a method[11] that consists of plotting the average calendar day flow for each day of the flood as bar ordinates of a width equal to the day interval. The approximate mid-points of the bars, except for the peak of the flood, are connected by lines to represent a continuous hydrograph that contains, as nearly as possible, the same volume for each daily runoff as that recorded. The upward and downward limbs of the hydrograph are then extended to such intersection on the day of peak flow as will give results for that day consistent with the known average daily flow.

W. E. Fuller[21] proposed an equation that has been frequently used to convert maximum average 24-hr flood discharge to peak discharge. It is also used to convert calendar day average flow to peak. This equation is

$$Q = Q_{24} (1 + 2 A^{-0.3})^2 \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which Q is the momentary peak discharge, Q_{24} is the maximum average 24-hr discharge, and A is the drainage area.

Studies of many more records than were available at the time of preparation of this formula have indicated that the use of this equation will give results that will be far from correct, for the reason that it does not include consideration of all the factors governing the shape of the hydrograph.

Respectfully submitted,

Subcommittee, Review of Flood Frequency Methods, of the Joint Division Committee on Floods.

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FRANKLIN F. SNYDER, Representing the Waterways Division
GORDON R. WILLIAMS, Representing the Hydraulics Division
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[21] "Flood Flows," by Weston E. Fuller, *Transactions*, ASCE, Vol. 77, 1914, p. 564.

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